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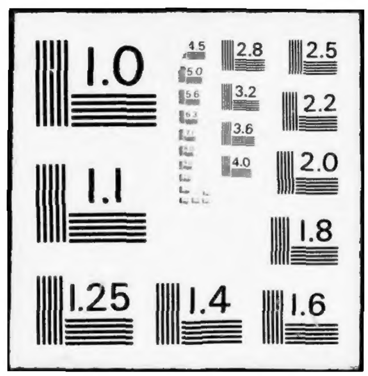
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HYPERSALINE LAGOONAL DEPOSITS AND PROCESSES IN BAJA CALIFORNIA, MEXICO

UNIVERSITY OF SOUTHERN CALIFORNIA, LOS ANGELES

APRIL 1976

REPORT USC-GEOL 76-02

HYPERSALINE LAGOONAL DEPOSITS AND PROCESSES

By

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Department of Geological Sciences
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Report based on work supported by
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IN BAJA CALIFORNIA, MEXICO

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ABSTRACT

Evaporite and algal-carbonate sediments are accumulating in coastal lagoons along the Pacific and Gulf of California coasts of Baja California and Sonora, Mexico. Laguna Mormona, 200 km south of the border, is on the Pacific coast of Baja California and is a closed lagoon lying behind a back-beach dune ridge through which water percolates to the ponds. Salina Grande is 180 kn south of the border on the Sonoran side of the Gulf and is a pair of sag ponds formed along a major fault cutting older Colorado Delta sediments. Water enters from the local water table and from the Gulf during highest tides. Laguna Ometepec, just north of San Felipe on the Baja California side of the Gulf, is a gently downwarped portion of the mudflats of the Colorado Delta and receives water from the Gulf at highest tided and when winds blow strongly onshore.

Mormona's sequence of algal mats and stromatolites is associated with gypsum. Salina Grande's outer pond is a salt rock-gypsum complex and the inner pond is gypsum and organic muds. Ometepec is a salt rock deposit with gypsum sedimentation dominant at the present surface. All three are

coastal pond facies of the classic sabkha sequence of the Persian Gulf, Red Sea and North African coast. They illustrate three examples of products of varying interactions of climatic-oceanographic-topographic factors within a large geographic province of dominantly detrital-terrigenous sedimentation.

Analysis of the cycles of deposition was made using three years of ERTS imagery with ground surveys to establish the ERTS analysis. These data plus field work document rates of sedimentation of the facies types. Fluctuations of sea-level and subsidence can produce cyclic vertical successions of marine marginal evaporite facies with terrigenous or marine facies. Although it is conceptually difficult to visualize their preservation, the geologic record shows stacks of such sabkha cycles of all ages and confirm Shearman's observation that "sabkha measures" of desert coasts are as significant as "coal measures" of more humid coasts.

INTRODUCTION

Hypersaline marshes and coastal salt flat environments are characterized by a myriad of complex meteorological, biological, chemical and geological interactions. Variability of processes is high; fluxes are visually perceived, yet difficult to quantify. This paper synthesizes available data for two coastal salt ponds and reflects on the implications as to cyclic or rhythmic patterns in paleoclimates and sealevel fluctuations. Emphasis is placed on the Mormona area of the Pacific Coast of Baja California with comparison to the intriguing, but difficult of access, Salina Grande ponds of the Sonoran coast ~~(Fig. 1)~~. A few comments are also included on the Ometepec Salina on the Gulf of California Coast of northern Baja California.

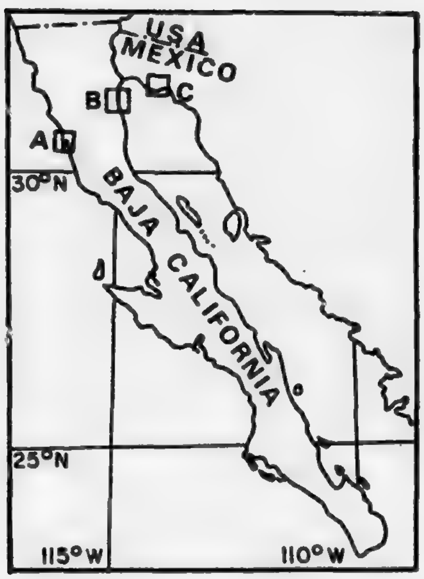

FIGURE 1 - Location of the areas studied. A is Laguna Mormona, B is Laguna Ometepec and C is Salina Grande.

REGIONAL SETTING

Laguna Mormona

The Laguna Mormona Complex is on the tectonically active Pacific coast of Baja California, (Gastil and others, 1971; Doyle and Bandy, 1972). A study of marine terraces and alluvial surfaces from Ensenada to El Rosario by Orme (1972) documents appreciable uplift, with accompanying tilting, which has resulted in a depressed hinge line trending approximately east-west about 25 km north of Mormona. Three prominent terraces in the area have been subjected to locally intense, near vertical faulting, often striking northeast-southwest, with less deformation of the lower terraces than of the older, higher ones.

The coast from Ensenada to El Rosario is comprised mainly of Cenozoic sedimentary rock, cobble terraces and minor amounts of Pleistocene volcanics (Gastil and others 1971). Landform classifications of the coast by Bale and Minch (1971) together with those of Wright and others (1973) include photographs of the Mormona Salt Ponds. Woodford (1928) along with Bacon and Carmichael (1973) briefly investigated the volcanic field that forms the southern boundary of the Complex. Gorsline and Stewart (1962) described the Quaternary geology of San Quintin Bay .

From accounts of Viscaino's expedition of 1602, there

were three Indian villages at San Quintin Bay (Meigs, 1935). The abundance of fish and clams made this area very attractive as evidenced by the numerous middens still found in the dunes. Collecting and shipping halite from the Mormona Salt Ponds have been of importance to the Indians, Mission populations, and the early Russian, Spanish and English navigators. These ponds have been worked continuously since 1926 by Mexican and American commercial groups that typically remove 1000 to 2000 tons per year.

The Mormona area is characterized by a semiarid or dry Mediterranean climatic regime. True desert begins 50 kilometers farther south along the coast. Oceanic weather patterns exert a dominant influence, and the role of the towering sierra San Pedro Martir to the east in deflecting storm systems cannot be minimized. Hurricanes may cross the coastline in the vicinity of Mormona, but usually confine themselves to the southern half of the peninsula and the Gulf of California. (Roden, 1964). Seasonal and diurnal fluctuations at Mormona are not as severe as those of the inland and Gulf areas of Baja California because of the moderating effect of cold offshore currents and moist coastal Pacific air. Precipitation and temperature measurements made during the last 20 years are summarized in Table 1. For the period 1919 to 1953 the region within a 50 km radius of Mormona shows up to 43% variability in precipitation from year to year (Fig. 2)

TABLE 1. Meteorological and tidal data [1], Laguna Mormona and Salina Grande areas.

CHARACTERISTIC	Salina Grande	Laguna Mormona
Tide Range:		
Mean	3.8 m	1.3 m
Spring	5.5 m	1.8 m
Max. Spring	7.0 m	2.8 m
Offshore Surface		
Water Temperature $^{\circ}$C	Ca 16°-19°C	Ca.14°- 19°C
Air Temperature:		
Annual Mean $^{\circ}$C	21°	15.5°
Annual Range (3 years)	not available	14.9°-16.2°= 1.3°
January Mean $^{\circ}$C	11°	12°
July Mean $^{\circ}$C	32°	19°
Minimum Winter Temp.$^{\circ}$C	-8.3°	not available
Winter Range	28°	" "
Summer Range	21°	" "
January Diurnal Range	19°	" "
August Diurnal Range	10°	" "
Precipitation:		
Mean (mm)	74	125
Annual Range (3 years)	not available	157

	Salina Grande	Laguna Mormona
Winds-direction and relative strength	Southeast-southwest (summer) Northwest North-Northeast (winter) (Occasionally South) Violent storms from South.	
	0-20 km/hr (summer) >20 km/hr usually during winter northerlies or from southerly tropic storms in summer	0-20 km/hr
Evaporation:		
Mean annual (lake) (cm)	not available	130cm [2]
Mean annual (pan) (cm)	not available	180cm [2]

1. Data from Thompson (1968), Hendrickson (1973) and Vonder Haar (1976)

2. Extrapolated from U. S. Weather Bureau records at San Diego, California

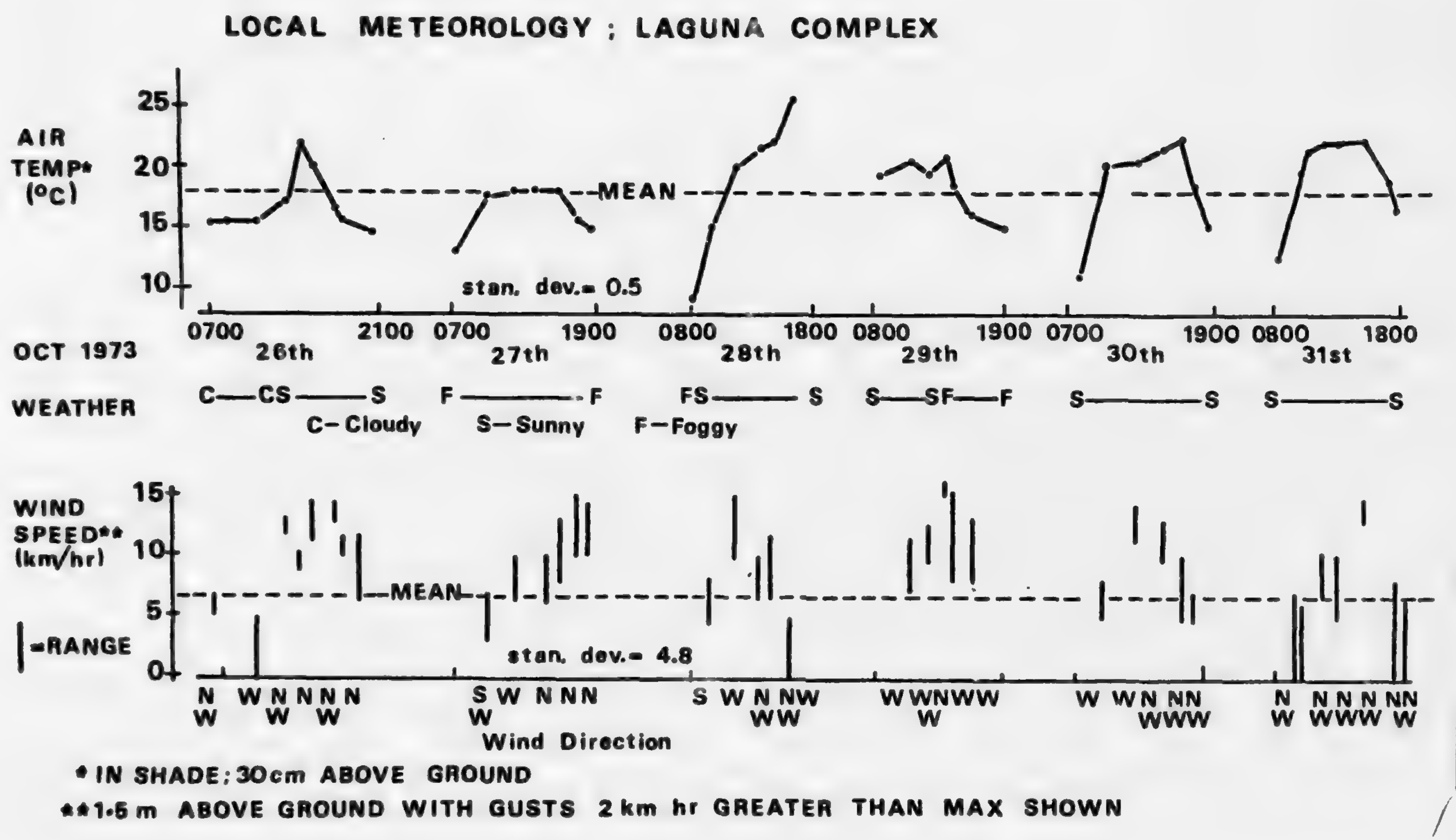

FIGURE 2 - Meteorological data for the Laguna Mormona area.

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(Bonnie and others, 1970). Intermittent fogs are a notable moisture source.

Winds are usually onshore from the northwest and begin in late morning with a maximum intensity in the late afternoon. Occasionally there is a constant wind that blows strongly for days from the south or northwest. Cloud cover is a function of daily formation of clouds coupled with occasional larger frontal cloud systems. Evaporation and precipitation data are approximations (see Table 1). The yearly water deficit (potential evaporation versus precipitation) is 42 cm at Ensenada (Wright and others, 1973), which is 100 km north of Mormona.

Salina Grande

A pair of sag ponds, called Salina Grande, on the Sonoran coast of the Gulf of California (Figs. 1 and 3) were noted in Merriam's (1965) regional study. He suggested that these small basins were a result of faulting of dominantly vertical displacement, associated with an extension of the San Jacinto rift system. Subsequent visits by Merriam and the authors discovered a series of aligned springs and linear ridges that give indirect evidence to an origin by faulting (see also Summer, 1972).

Mechel (1975) provides a summary of the geology in the Colorado Delta region and an orbital photograph of Salina

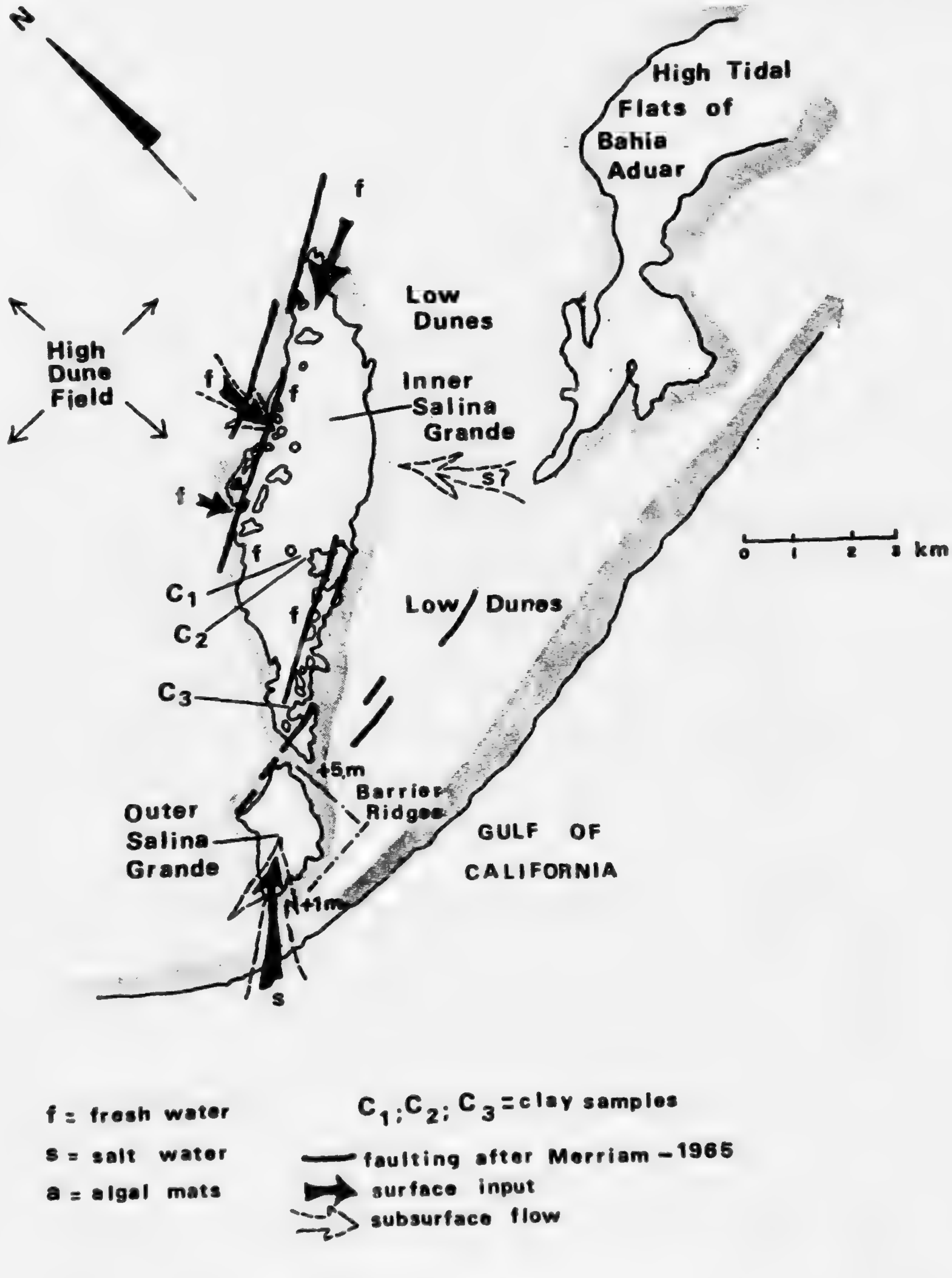

FIGURE 3 - Details of Salina Grande lagoon system, Sonora, Mexico.

Grande. Similar regional analyses with orbital imagery can be found in Stone and others (1973) in addition to Vonder Haar and Stone (1973). The principal features are the raised later Tertiary and Pleistocene deltaic and shallow marine deposits, large dunes on the Sonoran Terrace, the modern Colorado Delta and the tide flats of the terrace margin. Tidal range is of the order of 8 m at spring tide.

Henrickson (1973) compiled meteorological data during 1971-1973 at Puerto Penasco, on the coast 25 km east of Salina Grande (see Table 1). These data give some idea of seasonal cycles. While precipitation and the degree of cloud cover fluctuate locally, the skies are usually clear.

Winds blow from the southeast, south and southwest during April to September, and from the north, northeast and occasionally east during November to January. February, March and October are transitional and are notable for their variable wind directions.

Winds from the northwest, north and northeast are strong but highly variable. Winds from the south are commonly more than 18 km/hr and at times develop into storms. Westerly and easterly winds are usually light, through at least one storm was dominated by westerly gales. In general, the most violent storms are from the south and these generally occur in the late summer and fall. Blowing from the north or northwest,

winter storms are less violent; they create smaller seas, but are of longer duration.

LAGUNA MORMONA ENVIRONMENTS

The Mormona coastal complex consists of a series of environments that occur inland from the ocean in a sequence: near shore and beach, barrier and dune ridge, narrow marsh with algal mats, evaporite flat and salt ponds, paleodune hill-alluvial terraces (Fig. 4). We will not describe the marsh-algal mat sequence here (see Horodyski and Vonder Haar, 1975; Horodyski and others, in press).

Nearshore and Beach

A fine quartz sand (Table 2) with abundant heavy minerals is the dominant component of the beach; igneous cobble cusps and ramparts are present along about 20% of the coast near the seaward base of the barrier dunes. Biogenic components are of limited diversity and consist primarily of kelp and eel grass (*Zostera marina*) washed on to the shore, sand dollars (*Dendraster excentricus*) and Pismo clams (*Tivela stultorum*). Onshore winds transport sand across the beach to the base of the barrier dunes and then up the dune slopes. Storm waves extensively redistribute the cobbles.

In the nearshore zone, for about 100 m from the beach at low tide, quartz sand forms ripples and breaker bars, as off the coast of Galveston, Texas (Spearing, 1974, chart 5).

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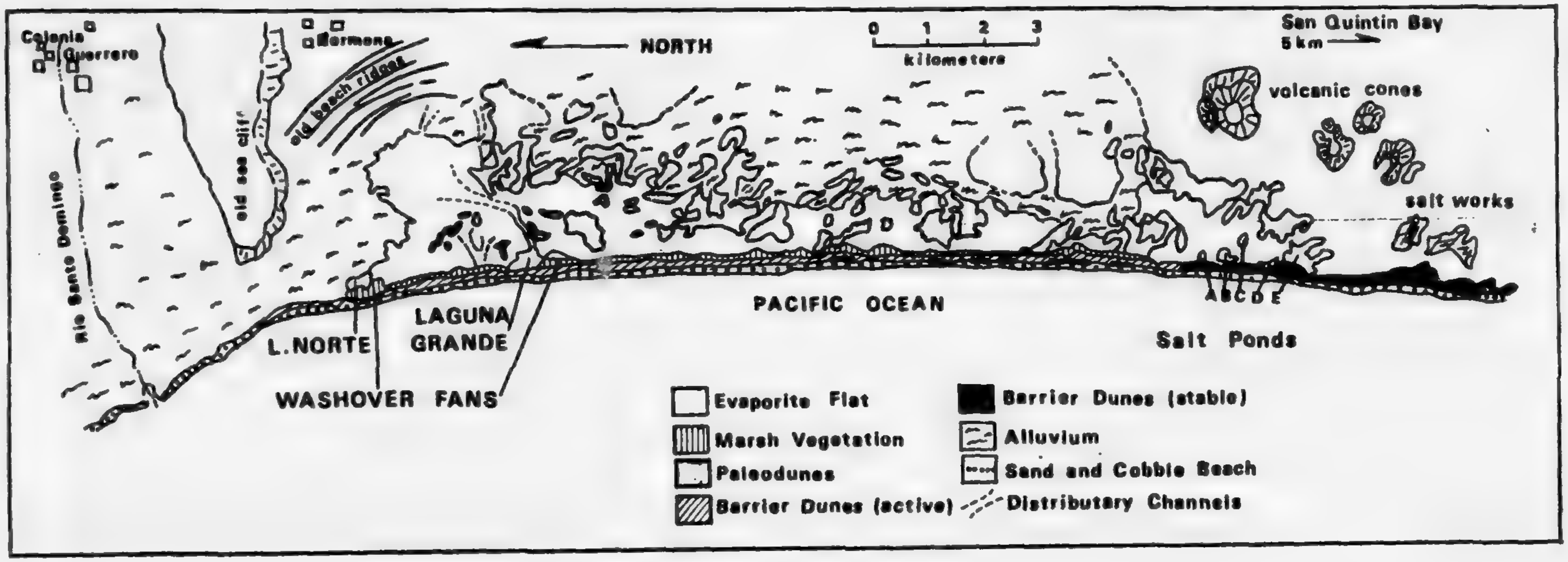

FIGURE 4 - Details of Laguna Mormona, Baja California, Mexico.

TABLE 2. Textural analysis of quartz sands at Laguna Mormona, Baja California, Mexico.*

LOCATION	Mean Size (mm)	Phi Standard Deviation (S_ϕ)
Active barrier dune	0.25	0.79
Stable barrier dune	0.21	0.85
Paleodune (after Orme)	0.19	0.97
Beach; lower foreshore	0.18	0.63
Alluvium; between paleodunes	0.12	1.02
Evaporite flat; basal units	0.14	0.75
	0.15	0.73
	0.22	0.70

*Representative values

Surface salinity and tidal range are listed in Table 1.

Aerial photographs show sediment plumes from the Rio Santo Domingo which are elongated to the south suggesting longshore current transport in that direction. Satellite imagery from ERTS and SKYLAB indicate turbidity that extends in plumes with widths of from 1.5 to 20 km seaward. Gyres of 0.7 to 1.5 km diameter are occasionally present about 1 km offshore and a single counterclockwise gyre of 5 km diameter is visible on 24 November, 1972. Continuity of the turbid zone ranges from very patchy to uniform, with irregular fingers that appeared to correspond to rip currents observed during field studies. Along the Mormona inner shelf region, from the Rio Santo Domingo to Isla San Martin and from the shore seaward for 20 km, a total of 500 km^2 turbid water covers from 10 to 50% of the region during various times of the year. No definitive correlation between turbidity or rip currents and lagoonal flooding or distributary channels has been established. These gyres and patches are probably decay fragments of the eddy system that exists off Cabo San Quintin and Cabo Colnett in September and January as cited by Robinson (1973).

Barrier Dunes and Washover Fans

A continuous zone of sand dunes 20 km long extends from the Rio Santo Domingo southward to San Quintin Bay. These form a linear ridge, which ranges from 6 to 12 m in height and 100 to 200 m in width and are an unbreached barrier that separates the Pacific Ocean from the marsh and salt flats of Laguna Mormona. Prevailing winds have shaped the dunes into distinct northwest-southeast trending traverse ridges and a coalescence of small parabolic dunes. A variety of plants, such as the iodine bush (*Allenrolfea occidentalis*) and hydrophytes stabilize the dunes, particularly the lee slopes. Approximately 20% of the barrier surface is heavily vegetated with some of the bushes reaching a height of 1 m.

The sand comprising the barrier dunes consists predominantly of quartz with 5 to 10% heavy minerals which accentuate the sedimentary structures. Internal stratification of these dunes resembles that described by Bigarella and others (1969) along the coast of Brazil, with characteristic tabular-planar type cross-sets that have low-to high-angle bounding surfaces. Sets dip downwind except for occasional avalanching sets on the windward slopes. Rainfall on the dunes forms runoff channels and liquified sand slides into dune hollows, onto the beach sediments and directly into the adjacent marsh. Pebbles on the seaward edge of the barrier

dunes indicate a maximum movement by storm waves of 1.5 m above the local mean sealevel.

Two units comprise the barrier dunes and these are termed the Active Barrier Dune and the Stable Barrier Dune (Fig. 4). Sands of the stable units form resistant cliffs; they are not migrating and possess a tan coloration, darker than those of the active unit. The Flandrian age of 3000 to 4000 years before present assigned to the active dunes by Cooper (1967) appears correct from the studies by Orme (1973b). Superposition of the active unit over the stable one and the more cohesive nature of the latter suggests that it is part of an older coastal complex.

On the landward side of the present barrier are two permanent semicircular lobes with segmented borders and wedge-shaped cross-sections that are believed to be washover fans (Fig. 4). Similar features attributed to hurricanes breaking through coastal dunes and depositing nearshore, beach and dune sediment are reported by Hails and Hoyt (1969) on the Atlantic coastal plain (see also Reineck, Singh, 1973, p.298). The quartz sand of the fan contains wood fragments, pebbles and shells that are presently deposited only on the beach, and a mixed assemblage of coarse sand lenses, bioturbated sections and well-laminated sediments.

Paleodunes and Alluvium

The most landward Mormona environment is formed of low, rounded hills of old dune sand (paleodunes), with interdune alluvium and ponds in the south (Fig. 4), gradually yielding to low alluvial terraces in the north. At the far southern extremity, the dunes surround present-day salt ponds. Isolated to clustered paleodune mounds that are 0.5 to 2 m high and 4 to 20 m long are present on the evaporite flat (Fig. 4). Ridges and troughs on the hills trend northwest-southeast (Fig. 4) and the hills themselves reach heights up to 10 m while averaging about 5 m. The northwest-southeast orientation suggests that onshore winds equivalent to modern directions were operating in the past. A series of old arcuate ridges in the alluvium at the north end of Mormona (Fig. 4) apparently formed on tidal flats during a previous coastal cycle.

Thorny Shrubs, grasses and hydrophytic plants grow on the paleodunes and alluvium. Stabilization of the surface by the vegetation plays an important role in the preservation of the mounds, in spite of rains, surface flooding and persistent winds. Within the last decade, an increasingly larger portion of the alluvium has come under cultivation.

The sediment of these features consists (Table 2) of a tan,quartz sand, rich in heavy minerals, and with about 5% organic material. Wind blown gypsum sand from the evaporite

flat accumulates on the windward side of the mounds and hills, where it is commonly mixed with the quartz dune sand. Cross-laminations and plant roots are the prominent structures in paleodune sediments, although trenching of some vegetated dunes to a depth of 1.1 m uncovered no distinct structures in the oxidized sand. Presumably the soil and rooting processes have obliterated primary structures.

No attempt was made to subdivide the paleodunes and alluvium other than to consider each a mappable unit. In comparison to the Barrier Dune units, the paleodune units are more vegetated, more cohesive and have a larger degree of staining on grains. Superposition indicates that the pale-odunes are older than both the active dunes and some of the lava flows of the San Quintin volcanic field. A pre-Falan-drian age has been assigned to the paleodunes by Orme (1973 a, b) based on comparative studies with other Baja California coastal dunes although no fossil or radiometric ages are available for Mormona proper. Dating of the San Quintin volcanics could provide the necessary ages.

Salt Ponds

Five salt ponds at the southern end of Mormona are isolated from the northern flat and each other by Paleodunes, which control the pond shapes. Each pond is occasionally filled with water to a depth of about 35 cm (Fig. 5A) and

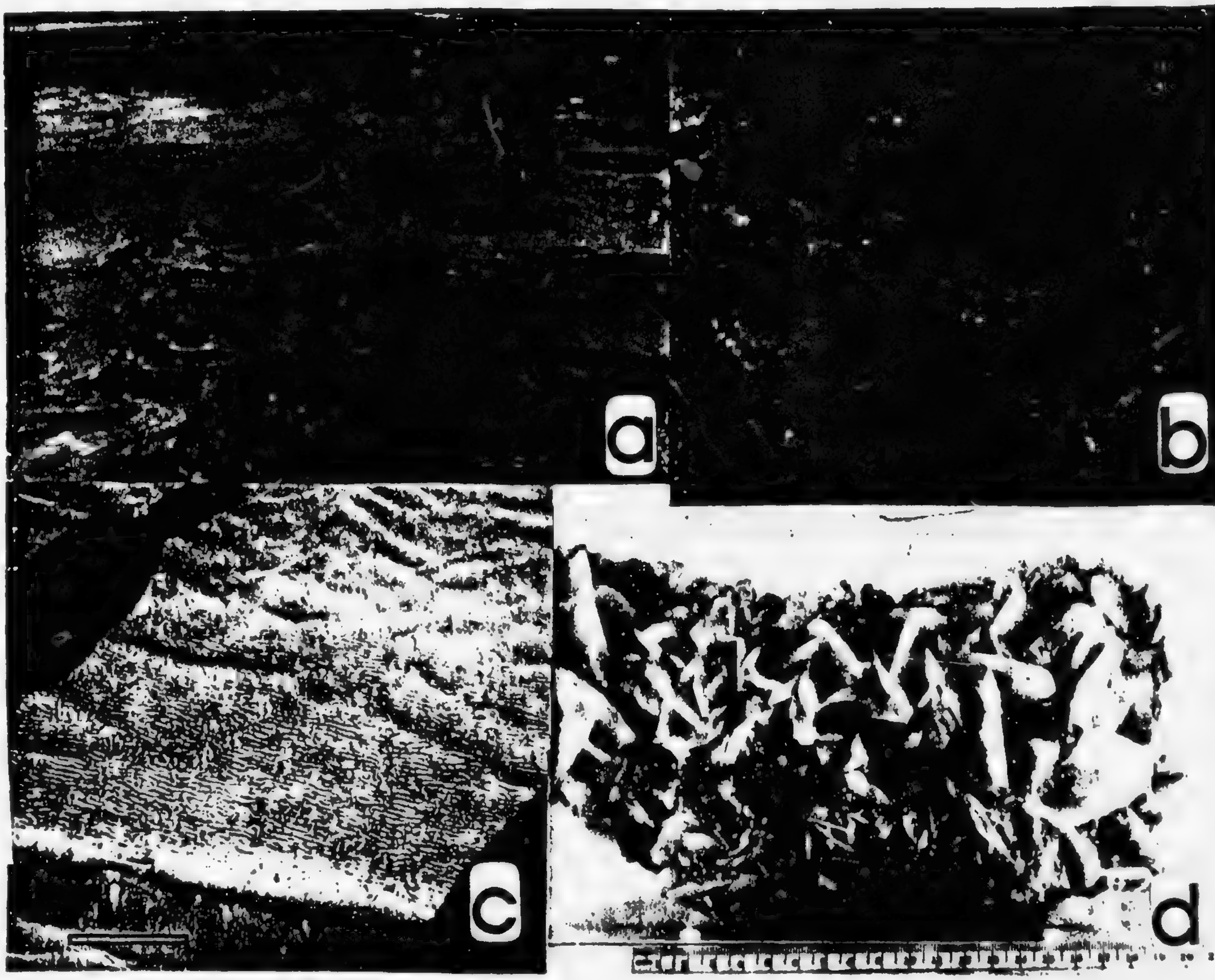

FIGURE 5 - (A) Salt pond "B" at the southern end of the complex showing subaqueous mounds and ridges of gypsum and halite hoppers and cubes (white) being deposited between mounds in June, 1971. Water depth, 35 cm, Scale near letter a is 60 cm. (B) Breached halite and gypsum ridges. Scale = 25 cm. (C) Portion of nonevaporite pond north of pond "B"; windward edge of central spit showing ripples, 2 cm length in 2-5 cm water depth. Scale = 30 cm. (D) Broken portion of gypsum mound showing tabular to lensoid crystals. Subaqueous environment; seaward edge of ponds.

at the deeper seaward edge to 90 cm. The bottom of the salt ponds contains no rippled sediment; microripples form only in the non-evaporative marsh ponds (Fig. 5C). This selective non-formation is attributed to a combination of higher paleodunes shielding the ponds from the prevailing winds and to rapid cementation of the pond bottom sediments by gypsum and halite.

Fluctuations in the areal extent of standing water contribute to the total water budget in the area and aid in understanding subsurface refluxing and evaporation-humidity parameters. Satellite imagery, primarily the infrared band of LANDSAT-1 (formerly ERTS-1), in combination with field observations, is successfully employed in our work in Baja California (Vonder Haar and Gorsline, 1975).

Because infrared wavelengths penetrate water to a depth of a few centimeters, there is a sharp contrast between water-covered surfaces and adjacent areas. On the basis of an analysis of the infrared band (0.8 to 1.1 mm) of the LANDSAT-1 multispectral scanner imagery, using a binocular microscope for zoom magnification, we were able to separate a given location (e.g. salt pond B) into three classes based on a quantitative optical gray scale: (1) black=standing water, (2) medium to dark gray=moist area, (3) light gray to white=dry ground. The areal percentage of each type of surface was

then determined (Fig. 6). While Figure 6 indicates the variation in flooding persistence between the northern Mormona gypsum flat and pond B, there were also variations among the ponds. At times the small pond A was completely dry while the adjacent salt pond B was entirely standing water, with ponds D, E and F partially moist, dry or wet. These variable conditions may persist for at least a month. As a consequence of this interpond variability, one should not expect to correlate rhythmic layering between coastal ponds tens of meters apart, or with a large evaporite flat a few kilometers distance. A paper in press by Vonder Haar treats this subject in greater detail.

Flooding frequency appears to be an as yet undecipherable function of highest tides augmented by onshore storms, which suggested that assumptions that ancient laminae are annual products may be erroneous as reported in Vonder Haar and Gorsline (1975). Shepard (1973, p. 68) noted that hurricanes can raise the water level along a shore to 4 m above mean sealevel, and tsunamis to 3 meters. During field observations at Mormona strong winds and waves from offshore storms have held water high on the backbeach for days, well above the mean seasonal tide.

The evaporite areas in the paleodune deflation hollows between the salt ponds and the San Quintin volcanoes (Fig. 4)

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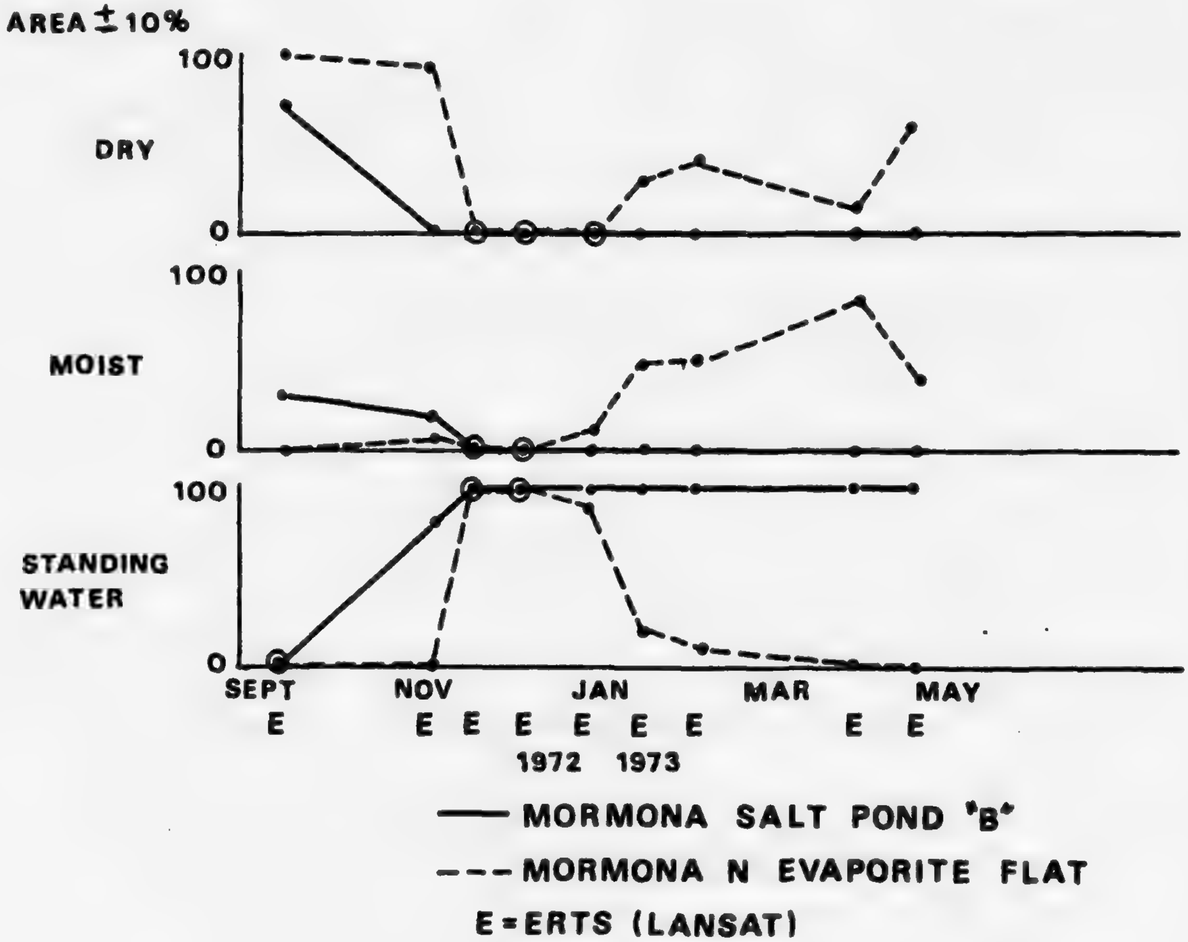

FIGURE 6 - Change in water-covered, water-wet and dry areas at Laguna Mormona from ERTS (LANDSAT) Imagery.

were not studied in detail. They are similar to the main flat in that they consist of crudely layered gypsiferous sand. They may, however, be more akin to continental sabkhas as described by Kinsman (1969) and Glennie (1970).

Biological activity in the salt ponds is not as meager as initially expected. Spiders, insects, worms, and brine shrimp are common. Blue-green algae and a pinkish material, believed to be bacteria, partially coat the evaporite grains in the crust from the surface to 10 millimeters.

Mineralogy and Geochemistry of Ponds

In their summary of physicochemical conditions of the origin of evaporites, Braitsch and Kinsman (in press) emphasized that many parameters are not presently known with sufficient precision. This study presents what geochemical data were readily obtainable from the ponds in the hope that it will aid in a rigorous chemical investigation in the future.

The fluctuating values of brine from Salt Pond B (Fig.7) are due to precipitation of halite, aragonite and gypsum and to dilution by less saline ocean water. In contrast to the brine chemistry illustrated in Figure 7 (April to August,1971) for January, 1971, the values for the sample 70 m from the west shore in gm/kg were : $Cl^- = 148.9$; $Ca^{++} = 0.72$; $Mg^{++} = 5.95$; $K^+ = 2.32$; $Na^+ = 21.48$; $Sr^{++} = 0.004$ and $Fe^+ = 0.0002$ (all to $\pm$ 2% of given value). Incorporation of Sr^{++} into the aragonite

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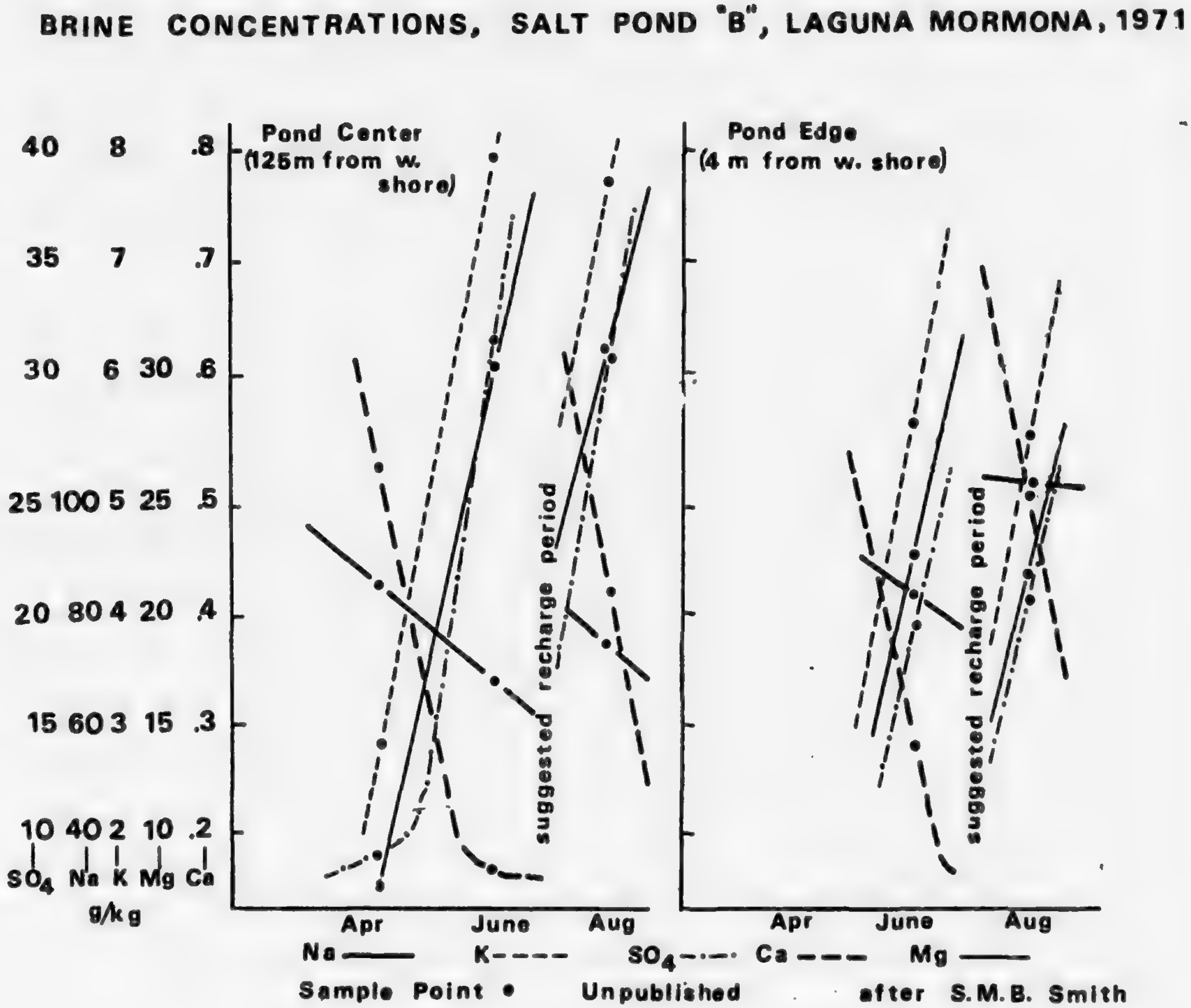

FIGURE 7 - Brine chemistry for Laguna Mormona ponds.

lattice at the elevated salinities may be the cause of its low concentration. A compilation of all data from all seasons at Pond B shows a Cl^- content from 111 to 160+ ppt (mean = 146; standard deviation = 15.8) and a K^+ range of 2.3 to 7.9 ppt (mean = 5.1; standard deviation = 1.81). The more concentrated brine tends to lie on the landward side of the pool. Evaporation of an enclosed basin produces increasingly more concentrated brines, which theoretically should move to the low parts of the depression. While this is always the case at Salina Ometepec (Fig. 1; S. M. B. Smith, personal communication), the lowest areas of the Mormona ponds, on the seaward side, are occupied by the least concentrated brines. This suggests that the ponds are recharged with ocean water that seeps through the subtidal portions of the barrier sand ridge. This lateral influx of seawater is analogous to the models proposed by Scruton (1953) and Briggs (1958) whereby simultaneous precipitation of two or more evaporite minerals can take place in different parts of a basin. The most soluble salts precipitate farthest from the point of influx. In pond B gypsum is the dominant mineral on the seaward side with halite on the landward side thus providing a small scale example of the model.

On some occasions the shallow water bodies in pond B were inversely thermally stratified with surface water some

2^{o} C cooler than the deeper water a few cm below the surface. This is apparently due to a density stratification due to separation of denser brine at the base of the shallow (few cm) water column before wind strirring later in the day mixes the thin water body. Friedman and others (1973) have reported similar conditions in a hypersaline pool on the Red Sea shore. Hudec and Sonnenfeld (1974) report a similar phenomenon in a small lagoon floored by gypsum in the Venezuelan Antilles. The brine pans can form excellent heat traps according to the above authors and can trap approximately 90% of the incoming solar radiation. The less dense water inflow at the surface preserves the density stratification until wind mixing occurs. In contrast to the solar input, the heat of crystallization from bottom-growing evaporite minerals is sufficient to raise the temperature of the water by a few degrees centigrade. Such temperature increases stimulate chemical change in the sediment and in algal/bacterial growth that may influence banding in the gypsum crystals and stromatolite layering. On June 3, 1971, pond H showed a K^{+} of 7.41 ppt 10 m from the western shore while pond B at the same distance and depth exhibited a value of 4.65 ppt illustrating the variability between ponds depending on water depth, rate of influx, etc. Pond H is also more persistently and more frequently briny than pool B, perhaps due to its slightly lower elevation.

Salt ponds at Mormona typically have a vertical (downward) sequence of 15 cm of brine, 1 cm of sunken halite hopper rafts, 4 cm of halite cubes that grew on the bottom, 5 cm of gray water-soaked gypsum crystals (a mixture of lensoid-displacement and prismatic types, Vonder Haar, 1975), and a basal unit of quartz sand that contains soft blebs and finely dispersed aragonite near its top. Within the basal sand at depths varying from 5 to 40 cm is an irregular duricrust similar to that described by Horodyski and Vonder Haar (1975) on the northern Mormona evaporite flat.

Tabular to lensoid gypsum crystals, some with a long diameter of 10 cm, form beautiful interlocked clusters (Fig. 5B) on polygonal ridges along the seaward shores of the salt ponds. These mounds, ranging from 10 to 100 cm in diameter, mostly grew upward into the brines and are primary bottom growths rather than displacement forms.

Intermeshed halite hoppers 1 to 10 mm on a side occur abundantly in the salt ponds during the late evaporation stage (see Smith, 1971) and are similar to those described by Illing and others (1965) on the Persian Gulf sabkhas. No halite is present at depth in the sediment. If the ponds behaved as a closed system, the sediments would contain approximately 20 times as much halite (or potential halite still in solution in the brine) as gypsum. The ratios are closer to 10:1, in

favor of gypsum. The lack of halite implies that it or its parent brine must leave the system. Kinsman has suggested (1973) that since halite can only precipitate when the mean relative humidity is less than 76% such humidity control may explain why many coastal areas that have greater humidities, especially at night, may be restricted to the calcium sulphate minerals only,this may be the case at Mormona. Alternatively, the Na and Cl may be removed by subsurface refluxing, or by precipitation at the surface with later removal by winds. This halite enigma has perplexed all researchers of modern hypersaline systems and has not been resolved for Mormona.

A common feature of the evaporite setting is a network of mounds and ridges in a variety of magnitudes and shapes. For example, closed polygons range from 10 cm to a few meters in diameter with connecting ridges 1 to 5 cm high (Fig. 5B). These networks are analogous to mudcracks (Reineck and Singh, 1973), and similar morphologies in the algal mats at Mormona have been analyzed by Horodyski and others (in press). The origin of these raised networks appears to be a combination of shrinkage of fine sediment, as happens with the chaotic gypsiferous mids of the Colorado Delta (Thompson, 1968, Plate 9; see also Kahle and Floyd,1971), shrinkage of algal films, and lateral compression by growth of evaporite minerals (Vonder Haar, 1976). At the Mormona salt ponds the open interiors and overlapping breached ridges (Fig. 5C) are being filled

by gypsum and halite which makes the ridges more solid and maintains the structure after re-solution of the halite. In the deeper seaward areas of the ponds the ridge networks are overgrown by concentric to irregular gypsum mounds (Fig. 5A and D), often with halite cubes on their flanks. For the only available samples, the brine from inside a mound was less saline than the brine surrounding outside (4.65 versus 5.70 ppt K^+) while the Ca^{++} and SO_4^{--} values were unchanged at 0.26 and 20.1 ppt, respectively. Schreiber and Kinsman (1975) describe similar domal ridges that are presently forming subaqueously in the artificial solar ponds in San Francisco Bay, California. A progression at Mormona from mounds, to ridges, complete polygons, multiple polygons, and then to isolated ridges as water depth decreases could perhaps be applied as a possible paleodepth indicator, but other areas fall less convincingly into the sequence.

SALINA GRANDE ENVIRONMENTS

Two ponds forming this complex are aligned east-west, away from the shore. The outer pond contains up to 1 m of halite and gypsum, that is deposited over dune and beach (?) sediments. Some surficial salt has been commercially harvested. Thin gypsum and halite layers in the inner salina are laid down over black mud filled with gypsum crystal aggregates, which in turn appear to be deposited over pleistocene deltaic silts and sands. Clay minerals were analysed in three samples. In a surface mud beneath an evaporite pressure ridge (sample C) the clays were 45% mixed-layer, 45% clay-size mica, and 10% kaolinite. Three subsamples at 15, 25 and 35 cm below the halite surface crust were studied and each subsample was of similar assemblage. 70% mixed-layer, 25% clay mica and 5% kaolinite. A third sample from a dry surface was 50% mixed layer, 30% clay mica and 20% kaolinite. This may be due to textural differences or to different proportions of wind transported material. Diagenetic effects of the influence of saline brines is possible but not probable.

Zones of marsh and thin algal mats, similar to those at Ojo de Liebre (Phleger, 1967) are near areas which field evidence shows to be receiving rainwater from the adjacent dune field and seepage along faults. For example,

a sample of brine standing in a 20-cm-deep channel floored with sunken halite hopper rafts near the center of the inner Salina Grande pond had 136 ppt Cl^- content and K^+ content of 3.15 ppt. At the same time, some 400 m south and 50 m from fresh water reeds, a surface sample contained 8 ppt Cl^- and $K^+ = 0.16$ ppt.

Analysis of orbital photography indicates major flooding pulses during the winter, with more frequent and more extensive flooding of the salina than the inner one. In March, 1973, anomalously, 34% of the inner flat was flooded, while the outer pond was dry (Fig. 8). Such a condition may reflect fresh water drainage from the surrounding dune field. The earlier Apollo and Gemini data also hint at dry periods during the early spring and summer.

The ERTS coverage, in addition to charting frequency of flooding and the length of time required for removal of standing water, suggests the processes and paths of flooding. Persistent topographic highs are mapable by the first occurence of halite on the surfaces. Flood channels and depressions as small as 200 m in diameter are accentuated in the MSS band 7 when water remains standing in them.

21,- a

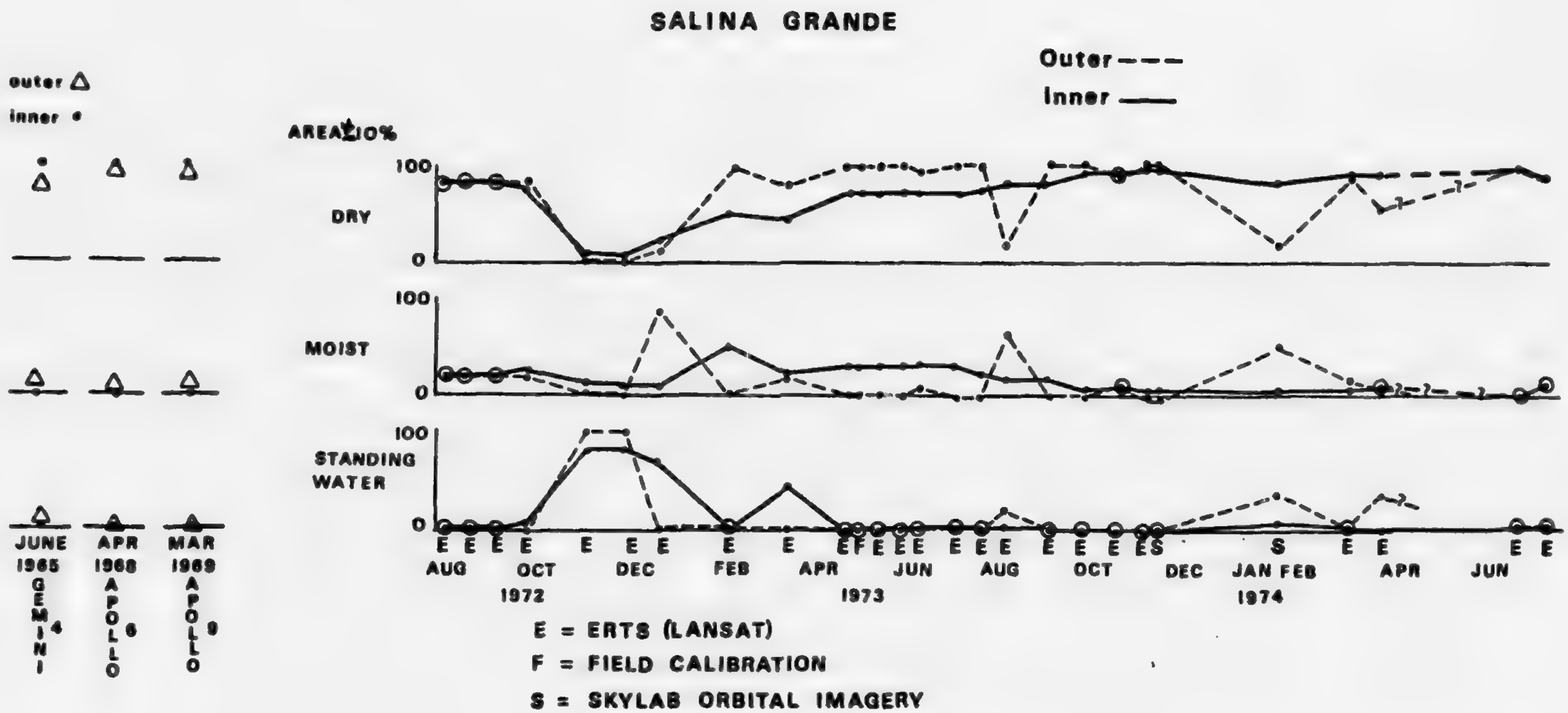

FIGURE 8 - Water-covered, water-wet and dry areas at Salina Grande from ERTS (LANDSAT) Imagery.

PRESERVATION OF THE FACIES; RECENT AND ANCIENT ANALOGS

The following characteristics of the coastal evaporites would be present in a lithified record of these sediments:

Dunes: cross stratified quartzose aeolinites; linear for kilometers where representing the barrier ridge but clustered or isolated where representing the paleodune hills and mounds; marked orientation of dunes axes in the direction of the paleowinds; extensive to low degree of root cast and soil formation.

Salt ponds: discontinuous, wavy to irregular laminated anhydrite with local traces of algal sheaths or kerogen; isolated anhydrite-halite lenses; anhydrite pseudomorphs of lensoid and prismatic gypsum crystals, blebs (= nodules) and rosettes of anhydrite all of which exhibit solution features; subaqeous anhydrite mounds and compression polygons; no dolomite, primary anhydrite or late phase evaporites; no fossils except displaced land gastropods, thus a paleontologic unconformity between the evaporite subfacies and the underlying more open marine lagoonal quartz arenites.

This flat-lying, thin and dominantly subaerial sequence overlain by redbed units of dune sandstones would perhaps be repeated in cycles. Fluctuations of either sea level or subsidence, would produce vertical cyclic successions in these

marine marginal evaporite facies with terrigenous or shallow open marine facies. As noted by Fairbridge and Kinsman (in press), these evaporite-tidal flat sequences developed on basin margins and therefore many were very likely destroyed: it is conceptually difficult to understand their preservations, but the geologic record shows many examples of such sabkha cycles of all ages. These confirm Shearman's observation that "sabkha measures" of desert coasts are as geologically significant as the "coal measures" of moister climes.

OTHER SETTINGS

Salina Ometepec, on the Colorado Delta mudflats, at the western side of the modern Gulf of California (Fig. 1), is the site of another stage in coastal evaporite mineral formation. Basal muds and quartz sands and silts containing prismatic gypsum (Thompson, 1968) are overlain by as much as 15 cm of gypsum, topped by a thin halite crust; locally a halite-gypsum rock up to 30 cm thick is present (Shearman, 1970; Smith, 1973). Anhydrite is not common but Kinsman (1969) and Butler (1970) reported both nodular and small felty types in limited areas. This region is comparable to Mormona in having a siliciclastic host sediment with adjacent alluvial fans, but is more susceptible to surface flooding from the Gulf of California (Vonder Haar and Gorsline, 1975) without the delay of seepage through a barrier. It is also an area of greater aridity. This aridity and the less permeable deltaic muds acc-

ount for the halite and anhydrite.

Other settings are: hypersaline ponds on the Gulf of Aqaba, (Friedman and others, 1973), coastal salt pans in Nambia (Cagle and Cruft, 1973), hypersaline ponds along the south-central Peruvian coast (Craig, 1968) and the 3 km-long lagoonal-pond on Carmen Island in the Gulf of California (Kirkland and others, 1966).

In addition, inland salt lakes (Eugster and Surdam, 1973) have some sedimentological features in common with marine evaporite pools. Zuni Salt Lake in New Mexico, as described by Bradbury (1971) is also similar in that it has algal mats, watery sapropel, interbedded halite, gypsum, calcite and organic material, as well as seasonal fluctuations in geochemical and biological parameters. However, although gypsum is a common mineral in lake sediments, it may be missing in some saline lakes because the chemistry of lake waters varies widely (Picard and High, 1972). Strakhov (1962) noted that the primary difference between gypsum formed in marine as opposed to continental environments is the increase in clastic interbeds and insoluable material associated with the gypsum in continental areas.

Ancient sabkha (= evaporite flat) sequences are numerous (Vonder Haar, 1976), but ancient coastal salt ponds are less often mentioned. There are some similarities between the

pond sediments of this paper and deposits described by Hardie and Eugster (1971), Bosellini and Hardie (1973) and the Deep Sea Drilling Reports for the Mediterranean and Red Seas (Ryan and others, 1973; Whitmarsh and others, 1974).

Comparison of these pond facies to other coastal locations reveals a spectrum of coastal evaporite environments. The climatic control for coastal evaporite formation apparently need not be as rigorous as Schmalz (1969) suggested; rather, wind and microrelief greatly influence the water budget and the brine concentrations.

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